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MELBOURNE, VICTORIA

Aircraft Structures Technical Memorandum 485

REPORT ON VISIT TO IFIP CONFERENCE, AALBORG, MAY 1987, ICASP5 AND SIX FATIGUE LABORATORIES (U)

by

D.G. FORD

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SUMMARY

During May 1987 the author presented a paper "Range-Pair Exceedances in Stationary Gaussian Processes" to the First IFIP Conference "Reliability and Optimisation of Structural Systems" at Aalborg, Denmark.

This memo describes this Conference, the better known ICASP5 and discussions at six establishments visited during the same trip.

DSTO ARL MELBOURNE

POSTAL ADDRESS: Director, Aeronautical Research Laboratory,
P.O. Box 4331, Melbourne, Victoria, 3001, Australia

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1. INTRODUCTION

In 1986 the author was invited to submit a paper to the "1st IFIP Working Conference" on "Reliability and Optimisation of Structural Systems" [1] at the Institute of Building Technology and Research at the University of Aalborg, Denmark. IFIP is the acronym for the International Federation of Information Processing and the Conference, between 6th and 8th May, 1987, was organised by their technical committee TC-7 chaired by Professor P. Thoft-Christensen.

Visits were also arranged to six fatigue establishments to discuss work in fatigue, especially fracture mechanics and crack growth. By a fortunate opportunity I was also able to attend the Fifth International Conference on Applications of Statistics and Probability to Soil and Structural Engineering (ICASP5). Many delegates attended both conferences. The subject matter [2] also overlapped but visiting both of them reinforced this while presenting a broader view of structural reliability.

1.1 Background

During 1985/86 I have been developing a program M-FREL for computing fatigue life distributions of structures with several cracks which interact in non-trivial cases. This is based on the theory outlined at the Weibull Conference [3,4] but computer capabilities have allowed significant extension. The executive, database and time-stepping parts of M-FREL are virtually complete and incorporate standard two-stage fatigue, damage tolerance with fixed and randomised initial cracks and intermediate models allowed by the presence of several cracks [5].

The remaining lower level segments to be created include a menu of cracking and damage laws, details of crack interaction procedures and attrition or risk of overload fracture. The invitation to the IFIP Conference was therefore an excellent opportunity to discuss particular cases at this and at other establish-ments. Because it was apparently further developed I decided to present some results about range-pairs at the IFIP Conference [6]. At ICASP5 there was more interest in range-pairs [7] although I had some discussion with Steen Krenk at Aalborg.

2.1 Institute of Aeronautics, University of Pisa (Friday, 24th April, 1987)

My main purpose here was to discuss the results of their work (Grant DA ERO-78-G-107) for the United States Army and similar more recent work on fatigue, fracture mechanics and crack growth for built-up stringer-sheet structures. This has been discontinued but discussions with Professor Salvetti, Dr's Lazzeri and Frediani greatly clarified their reports [8,9]. Professor Salvetti said that this would be updated.

These discussions were arranged during a preliminary visit which also scheduled some time for the ARL reliability and range-pair work. On the day originally planned Salvetti was at Aeritalia in Naples. The Institute is acting as a consultant for the AMX and ATR42 projects which are also associated with Aeromacchi and Embraer of Brazil.

Their particular interest is in the design of bonded panels. On the Wednesday I was shown some of the testing for these, other industrial contracts and some aluminium-lithium specimens.

The University work discussed on Friday 24th was mainly about cracking of stringer sheet structures. There was also a short description of Frediani's [10] use of isoparametric co-ordinates for computing 3-D J-integrals by finite element methods. The procedure is elegant and robust with respect to element size. It is known that along a crack front the J-integral is the sum of a surface integral and a local Rice type of line integral. When these are computed in terms of co-ordinates for 20-node elements it is found that 1/4-point or extremely small elements are not needed. Crack fronts are placed at the joins of 4 adjacent elements.

Poe's [11] original model for stress intensities in reinforced sheets was restricted to concentrated stringers with no allowance for out-of-plane bending. Work at Pisa began in 1973 with finite element analyses [8]. This was followed by extensions of Poe's model to incorporate 2 bending moments in stringer stiffnesses for an effective area [8]. The Douglas model for stringer flexibility was also improved and it was discovered that this was significantly affected by the elongation of holes during fatigue. In an application of M-FREL this would be a significant damage parameter to be modelled as a pseudo-crack.

It was found possible to include friction forces between stringers and the sheet but the accounting was very complicated with no practical improvement in intensity prediction.

The considerable experimental work in this project was divided into two parts:

1) Matching da/dn and ΔK predictions under constant amplitude. This led to flexibility corrections to the Douglas-McDonnell formula [12].

2) Further testing for correlations between constant amplitude and random load data. This involved best-fit Wheeler parameters associated with best Forman parameters for the basic da/dn data.

It was found that the scatter factor of two recommended by the damage tolerance report MIL-83444 was not always conservative.

2.2 Materials and Structures Department, Royal Aircraft Establishment, Farnborough (Thursday 30th April, 1987)

I was met by Peter Adams, head of Airworthiness Division, MS1. He said that Dorothy Holford whom I had hoped to see was at the Madrid meeting of AGARD (like Salvetti) in particular to hear a presentation by a Dr Stuck from FRG about characteristic manoeuvre sequences. Peter said that the method was oversimplified and that his feeling was shared by those in Messerschmidt-Bolkau-Blohm. I spoke to Brian Perrett and (Peter Adams) about the range-pair paper [6] for IFIP and left some copies. The number of staff at RAE has fallen and competition for graduates from computing firms has made recruiting difficult.

In the afternoon I saw David Rooke who spoke of intensity solutions and the RAE investigation of fretting. To answer a question he said that he did not plan to update Rooke and Cartwright [13] since more recent references, such as Murakami [14] were more comprehensive. However "If you read all the literature you wouldn't have time to write any books" and he thought that not all known solutions were in the standard compendiums. His theory on compounding, from Southampton, has recently been published as a book [15] and I also saw the latest summary of the compounding method [16]. He also said the boundary element method was attractive and useful but its reputation has suffered by the propagation of poor programs.

Roger Fenner at the University of Southampton is apparently using BE methods with Beukner singular fields [17,18] and also Rooke, Cartwright and Aliabadi [19].

Dr Rooke promised to send a report [20] of the most recent RAE results on fretting fatigue which are now being applied to lugs. It was stated that the general phenomenon could be appreciated in terms of a crack in simple strips. (Fig. 1)

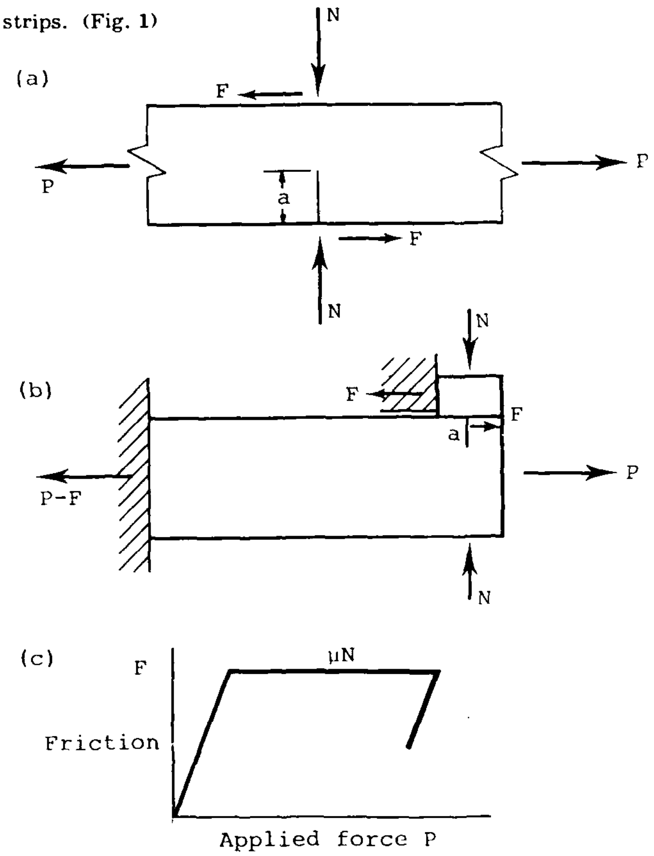

FIGURE 1 - FRETTING FATIGUE MODELS

In the notation of the figure there are direct and frictional components of intensity proportional respectively to $\sqrt{a}$ and $1/\sqrt{a}$ so that the dominant term depends on crack length. There is also a phase difference between frictional and direct intensities with forces selected as in Figure (1c). This may mean that additional turning points are introduced. As I mentioned, this can happen in other fatigue situations notably the buckling cracks in the wing leading edge of the CT-4. The report to be sent describes these effects in detail together with the 3-D application of singularity subtraction, related to a procedure of L.S.D. Morley.

The last visits of the day were to Dr's Graham Dorey and Chris Peel of Materials Division (MS4) who specialise in Composite Materials and Aluminium Alloys. The composites section is developing fractography for failed composite structures and working with Rhys Jones of ARL, using some locally developed programs. Dr Dorey mentioned reverse interactions which could be tailored to reduce loads in helicopter blades and forward swept wings. Helicopter blades commonly use GFRP rather than carbon fibre for superior damage tolerance. Dr Peel is also interested in fractography and I was also shown examples of Aluminum-Lithium Alloys, superplastic forming with fine-grained material and precision die forming (PDF). (There was also some superplastic forming at Rockwell International, Section 2.7). These processes are applicable to Aluminium-Lithium Alloys which are structurally similar to copper-based alloys with similar heat treatment. ALCAN has been licensed to manufacture one of the RAE alloys which is selling well in North America and Europe despite a price around 2½ times that of the alloys being replaced. Dr Peel said that the cause was lack of competition.

2.3 **IFIP Conference, University of Aalborg** (6th - 8th May 1987)

The program and a list of attendees are shown in Tables I and II. As a gathering by invitation, though not all arrived, the IFIP meeting either included or mentioned all experts known to me and many more that were not. All the European oil producers were represented and of course North America and Japan. Before discussing the conference a brief review [21] is in order.

In the modern approach to structural reliability complete evaluation of the risk over many dimensions is not normally attempted. It is assumed instead that all variables of interest (parameter space $\mathbf{X}$) are normally distributed, if necessary after transformation. The parameter space is then dichotomised into safe and unsafe regions $G(\mathbf{X}) \leq 0$ or otherwise where G is usually defined piecewise according to the various failure mechanisms to be considered (Yield surfaces are typical cases).

It is then assumed that one failure mechanism provides most of the risk. Technically, one performs a Rosenblatt transformation

$$\mathbf{X} \rightarrow \mathbf{U} \quad \text{where} \quad \mathbf{U} = \{U_1 \ldots U_k\}$$

and $U_i \sim NID(0,1)$. This obviously requires eigenvectors or the equivalent and the procedure in other fields is far from new. With this mapping the safety condition becomes $g(\mathbf{u}) \leq 0$; the reliability index is defined as $\beta = \min \{|\mathbf{u}| \,|\, g(\mathbf{u}) = 0\}$ and the actual risk must then be less that the normal probability $\Phi(-\beta)$.

The parameter space is usually a mixture of geometric, load and strength variates and, as in classical reliability theory, the mechanisms of failure are usually investigated as a tree of failures, often combined with plastic limit analysis.

Current research and developments should be fitted into or extend this framework. In $\mathbf{u}$-space the choice of β is effectively a choice of failure mode and open to engineering judgement, approximation and the methods of limit analysis. In framework, dimensions up to 50 are common so that it is often deemed adequate not to proceed past the first or second component failure (FORM or SORM).

Reliability, especially fatigue, depends on time so that much effort is expended upon the probability of first passages of $g(U|T)$, say, past zero. Load statistics, modelling and estimation were therefore treated by several authors at both conferences.

One development that has excited some interest is called β-unzipping [22]. In principle one starts with any unit load vector and increases it until first yield after which "a giant ten armed octopus" (Ditlevson [2] 1 p. 1) fixes that plastic hinge and loading continues. Successive hinges are similarly fixed and for plastic yield lead to the least safe ultimate load vector and β. At the conference this was the subject of several papers. These tried to extend the procedure, to brittle failures for example, but Ditlevson disagreed with some of these.

2.4 Departments of Civil and Mechanical Engineering, University of Waterloo (13th - 14th May 1987)

At Waterloo most discussions were with graduate students and the remainder with Professors D.J. Burns and Tim Topper of the Mechanical and Civil Departments. I was told that their policy of sandwich instruction has been instrumental in attracting students with the eventual effect of better students, more local industry and an increase in population which had joined four originally small towns. The main speciality at the University was computer science (WAT IV, WAT V etc).

David Burns first showed fatigue tests on tube joints for off-shore rigs. Major diameters were typically 1 metre and various levels of simulation were used up to sea water environment for an actual joint. This was largely co-operative work with Denmark (Neils Lind is from Bornholm). Along the fillet-weld crack growth at 1 cm intervals was measured by a pulsed DC potential drop (DCPD) technique. The equipment is calibrated by measurements of current in foil and boundary element solution of the Laplace equation for current. Conformal mapping was also used. These were basically two-dimensional techniques but the student describing this mentioned allowances for side leakage and interactions.

On Wednesday afternoon I lectured about the development of M-FREL. I found myself concentrating upon the Weibull paper [4] with computing references confined to data structure, fitting and integration of the crack-damage equations. On other occasions I spoke of range-pairs and the linked-list algorithm for reconstitution [5].

On Thursday I was introduced to the Ph.D students Paul, Jacques and David DuQuesnay. The first project is the prediction of life in 45^{o} buttress threads. From the time of Sopwith much has been known about local stresses without cracks and the load distribution among the threads. Paul's project is to use weight or Green's functions (supplied by Jacques) to compute stress intensities then crack growth and life. At present the pre-crack stresses assumed for semi-elliptic cracks are far too conservative because of the rapid decay of concentrated stress away from the thread-roots.

$$G(x,y) = \int \frac{dA}{L^2 \sqrt{\int ds/\rho^2}}$$

$$L = \rho_{min}$$

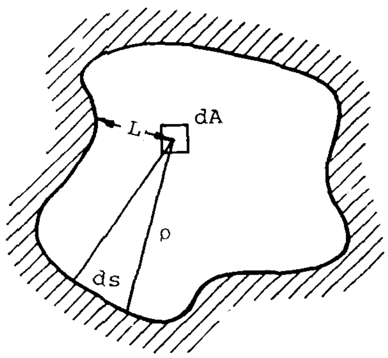

FIGURE 2 - BURNS WEIGHT FUNCTION

The project of Jacques was to extend the Burns [23] weight function (Figure 2) to edge cracks. This is exact for penny shaped cracks and good for many others but edge cracks present problems. There is now a program which reduces much of the past discrepancy caused by poor numerics.

His other project concerns unequal cracks in annuli eg. gun barrels. Here, if one crack exceeds the others these are shielded but intensity opposite the major crack is increased. When the cracks are dense the effect resembles a local reduction in thickness (and effective length) with a similar effect at 180^{o}.

I finally saw David du Quesnay who has been improving a Ford (Dearborn) program for Neuber analysis. We discussed randomness and the Bastenaire interpretation of damage and I promised to send him some references [24, 25].

2.5 **Institute of Theoretical and Applied Mechanics, University of Illinois, Urbana** (Monday 18 May, 1987)

At the Talbot Laboratory I was met by Professor R.T. Shield who had arranged visits to T.G. Shawki, F.A. Leckie, Kurath, D. Socie, Doug Marriot and very briefly, Dr K.S. Kim.

From Brown University, Dr Shawki was interested in plastic instability in terms of the stability of the governing differential equations for plasticity. He said that the commonly used linearisation of these can mislead about stability and quoted the example

$$\mathbf{Du} = \begin{vmatrix} -1 & e^{2t} \\ 0 & -1 \end{vmatrix} \mathbf{u}$$

solved by one Rugenius.

Unlike the case of elastic instability the reference condition for the perturbation equations alters with time. He thought that testing an energy norm

½ d/dt $(\mathbf{u}.\mathbf{u})$ was a better procedure and said that the Lyapunov method could also be misleading for non-autonomous equations.

Dr's Socie and Kurath work together on multiaxial fatigue. For infinite life the rules established by Gough [26] still hold but finite life is now an area of research. Experiments at the Talbot Laboratory use specimens with combined tension and torsion - some with pressure as well. Darrell Socie said later that their project was going well. Prediction was a matter of considering shear and tensile damage on all planes in order to define that of the initial crack which is important for subsequent cracking. Miner type damage leads to reasonable results for random loads.

Professor Fred Leckie began with an enquiry about load histories of some Victorian rail bridges being investigated by Paul Grundy at Monash. He is a material scientist, manager of his department and has a student studying Inconel. His main interest is dislocation pile-ups and local stress-strain relations within grains from which he hopes to predict cyclic relations for the macroscopic material. He knows of Brian Cox [27,28] Section 2.7, whose interests are similar.

On general fatigue he said that "most fatigue can be designed out", but stressed the importance of statistics and on-site evaluation though he acknowledged that this was impossible for many mechanical components such as shafts. If failures in these could not be removed by modification the Basquin Law, $(\Delta\sigma)^{1/10}N = \text{Const}$, indicated the dramatic improvements possible with reduced loads.

Professor Doug Marriot was interested in reliability theory or rather its failures; this topic was discussed later at ICASP5 [29,30]. He said that the Warner diagram (comparing densities of strength and load) often led to the false assumption that these were always independent whereas, in fracture for example, the metalurgical structure which caused a low K_{Ic} meant that corresponding K values were as harmful as larger ones in better material. Also in poor material the very density of incipient cracks was greater, heightening this effect. He was also interested in rogue events and a typical cause about which he has written. When I spoke of the problems of calculating without a model as I did at Tacoma Narrows to Dr Pidgeon he said that reliability could still be estimated although it became harder. His references [31,32] on this were similar to the Melchers models apart from detailed events. Near this time I admitted to independent damages in M-FREL pending the development of all the program.

Another interest of Professor Marriot is simplification of fracture mechanics about which he presents short courses. Some typical items for these are shown in Fig. 3. Because all practical cracks have curved fronts (thumb nail) the edge connection factor 1.1244 is always excessive. Similarly if a/b for semi-elliptic cracks is finite and the depth a $< 0.4T$ then back-wall effects cease to exist. In figure (3b) the approximate intensity reflects the greater importance of nominal stress at crack tips.

I finally spoke briefly to Dr Kim who works for Leckie. He is a ceramicist who studied at Brown under Serashi and he is engaged in developing joints between stabilised ceramics and Inconel. He seemed more interested in my area of fatigue and we spoke of polymer fatigue, Wolfgang Knauss, fracture mechanics [33] and the reversal in polymers of temperature and rate dependence effects as temperature rises. He also explained the role of cracks in the unstable combustion of propellant grains.

2.6 School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana (Wednesday 20 May 1987)

I was hosted here by Professor Alten F. (Skip) Grandt Jr. who introduced me to some of his staff at Grissom Hall (after Gus Grissom) and showed some of the fatigue testing near Lafayette airfield. All this was in the group Theoretical and Applied Fracture Mechanics.

Despite its name Purdue, like Illinois, is one of the large American state, land-grant universities which has the third largest U.S. aeronautical engineering school. They are especially proud of their connection with the space program and their graduate students normally include one or two RAAF officers. One of these is Flight Lieutenant Kevin Walker who proceeds next to Warner-Robbins AFB, GA. His project here is to test the value of placard limitations for fleet fatigue management using CRACKGRO and experiment. We also spoke of the Janus glider test at RMIT.

I did not meet the other RAAF student Flight Lieutenant Adrian Morrison who is developing a program FESENT for computer control of testing.

I spoke next to Dr Tom Farris who is investigating the change from benign flaking cracks in steel rails to serious ones perpendicular to the axis.

The mathematician in the faculty was Dr Martin Ostoja-Starzewski [34] who is applying random graph theory to modelling grain structures. This resembles the computer simulation procedures of Cox et al [27,28] whom I mentioned. Some theory for this appears in Vanmarcke [35].

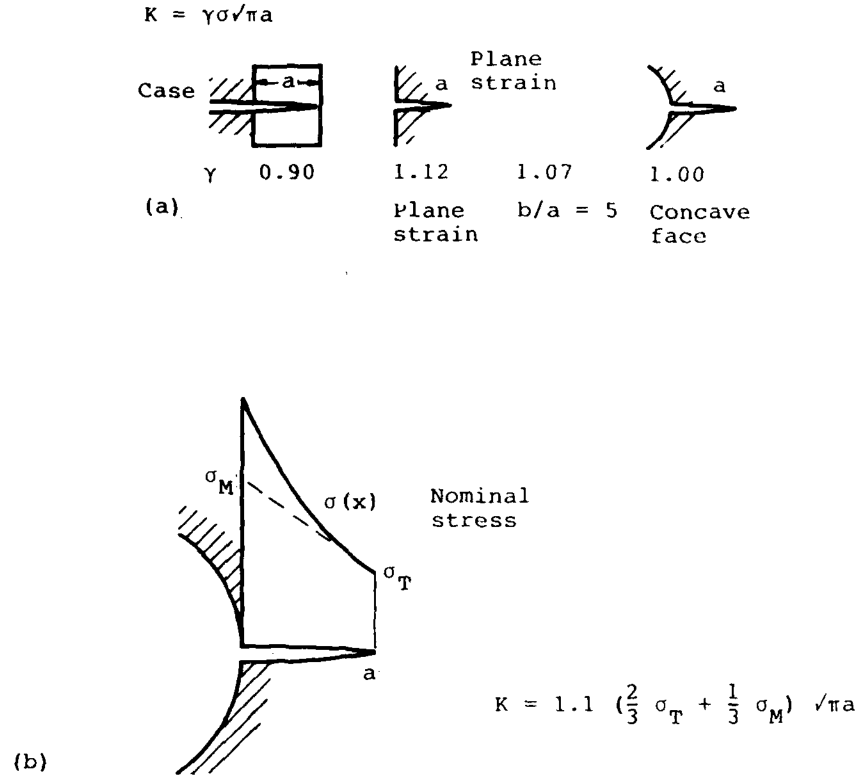

FIGURE 3 - APPROXIMATIONS FOR STRESS INTENSITY

Until the arrival of Jack Bogdanoff, now Professor Emeritus, I described the range-pair paper [6]. Martin indicated a related reference to be published by Macha [36]. Bogdanoff spoke of size effects, damage and related matters. The classical Weibull model of size effect is a weakest link theory of IID elements in series which begs the questions of defining the ultimate element and the joints between them. In his thesis at North Carolina, Pikiata [37] has developed another model in which the weakest flaw is chosen from a spatially Poisson density over the object of interest. This has been applied to long, thin continuous fibres and the length/strength relation for yarn is better represented thereby.

This led to the topic of accelerated testing and the need for at least three levels of acceleration. I was also told of a summary of fatigue crack theories to be presented by F. Kozin at a coming SMIRT Conference. There was finally discussion of irreversible thermodynamics - harder to follow than the size effect models. The essential point was that crack length was not the only measure of "damage" but other observables were also important; plasticity has also been followed and temperature investigated, the latter by Luccia and Volta at ISPRA.

At the airfield laboratory Skip and his student Ed Tritsch showed fatigue tests on plexi-glass (perspex) models in which the visible cracks allowed photography of interference fringes for analysis of crack opening and closure. From FEM analysis he has developed the formulae for interacting and joining thumbnail cracks which drew me to Purdue. This will be extended to generalise Newman's results [40] to three dimensional or thick-plate cases. The experimental results were quite well predicted from the postulated intensities by a program written for the test configuration with crack lengths described by depth and surface "lengths". This experience here has allowed Skip to find practical estimates of intensity from nominal stress distributions and weight functions and thus avoid FEM analysis and grid generation.

Before leaving I was also shown a crack growth test of grooved specimens [ASTM] and some results for Al-Li alloy reported in Fatigue 87 [41].

2.7 Science Center, Rockwell International Corporation, (Friday 22 May 1987).

Owing to delays there was less time to spend at Rockwell, but nevertheless I was met by Dr Brian Cox in the morning and delivered another lecture about M-FREL which was well received.

The Science Center at Thousand Oaks on US 101 is a separate branch of the Rockwell corporation which is expected to be profitable in the commercial sense though much of their income comes from government research contracts. However, much of their work is basic, a counterexample to those who would (sic) "make science relevant".

I was met by Dr Brian Cox and after the lecture spoke to A. Mike Mitchell, Roberto Kuegel, W. (Fred) L. Morris and John Richardson. Dr Cox spoke of the team's simulation work for small cracks in structured materials and presented some references [27,28]. Mike Mitchell showed me one of the test laboratories. One of the tests was in liquid nitrogen, another concerned metal matrix composites whilst there was also automated collection of da/dn-ΔK data from compliance and load control equipment.

Fred Morris spoke of debonding around nearby fibres in composites [43]. John Richardson and I discussed the life distribution implications of crack joining, especially the relation to runaway cracking or the ARL-NERF term r_F, continuity of probability and the possibility that rapid coalescence would smooth the local density of life. The context for this at Rockwell is the joining of many cracks in heterogeneous grains. This will be an extension of the teams present work [27,28].

2.8 ICASP5 Conference, University of British Columbia, Vancouver, BC (25-29 May 1987)

The lists of papers and attendees are shown in Tables III and IV. Because of the large numbers the conference was divided into three, sometimes four, separate sessions one of which was concerned with structural systems as at Aalborg. Other sessions dealt with geomechanics fatigue and random dynamics. Two topics with several papers were wooden structures and human fallibility [29,30]. In these 'soft' studies the papers of Rosenblueth, and Ingles were also interesting. The first [44] was largely about the ultimate cost of the Mexico City earthquake *whilst Owen Ingles* [42] included a plea for consistent language in the discipline. Other papers of special interest to me were Winterstein [45] and the elegant probability theory of Thayaparan and Karen Chou [46].

In the area of fatigue, Rackwitz [47] and co-workers are investigiating random processes which exceed several bounds, related possibly to SORM.

3. STRUCTURAL SYSTEMS AND AIRWORTHINESS

During the past decade structural reliability has developed considerably and it now has its own jargon (Ref. Owen Ingles at ICASP5 [42] and a quite standard notation. As stated by Neils Lind at IFIP the discipline "is a healthy adolescent" centred on civil engineering especially as an extension of plastic limit design. The other technical prop is the theory of continuous random processes and the associated statistics. Because of this extensive development and because the core of standard theory assumes multidimensional "structural systems" it is suggested that up-to-date airworthiness engineers should adopt the notation and language and adapt the theory.

Some shortcomings remain. These are:

1) Genuinely representative load cases. Probabilities can be conditioned for unlikely premises.

2) This can be accentuated with β-unzipping and design code cases can be unsuitable.

3) Like mechanical or electronic reliability it is essentially based upon discrete components even when fatigue is considered. In structures this is typefied by applications to frameworks. M-FREL avoids this by considering critical points or hot-spots rather than components.

4) Standard theory is also essentially static. Even in civil engineering, brittle failures seem to be a problem. Fatigued structures are treated as collages from a predetermined set of component histories; again, dynamic changes are basic to M-FREL [4,5].

These matters were addressed of course, especially at IFIP. In fatigue and expecially crack growth aeronautical experience may be useful to structural reliability. The civil engineers I met are aware of this but some felt that airworthiness engineers were mesmerised by retardation models.

It may be possible to divide the field into different schools. If so one of the most successful has the axis Munich, Denmark, VERITEC and Waterloo which have contributed to the development of PROBAN. The main figures here are R. Rackwitz, P. Thoft-Christensen and H.O. Madsen [50] of VERITEC and direct effort on the program exceeds at least five man years. (For comparison aeroelastic programs at ARL have been developed for at least 10 MY). Much of the theory has been developed by Ove Ditlevson of Lyngby who stands slightly apart from this school, being especially critical of β-unzipping. Other groups in the field are formed by the Institute for Risk

Research at Waterloo (Neils Lind) and the Americans such as Corotis, J.N. Yang, Wen and Vanmarcke.

CONCLUSIONS

Reliability analysis of structures is most developed in the design and assessment of civil engineering structures particularly oil drilling platforms and response to earthquakes. In these areas the state-of-the-art FORM-SORM technology has mainly been applied as a statistical extension of standard plastic limit analysis. Most of the leading investigators attended at least one of the two conferences visited; the groups centred at the Technical University of Munich and the Universities of Lyngby, Aalborg and Waterloo and Trondheim are important because they co-operate and are closely connected with VERITEC and fatigue testing of platform designs. The associated names are shown in References. The computer programs, especially PROBAN from VERITEC may include fatigue but this seems to be done on the basis of discrete components reacting at fixed times in accordance with predetermined histories. Therefore there is a place especially in aeronautical applications for the type of random dynamic interactions embodied in M-FREL. However the practical computation of failure risks in several dimensions/components is far more advanced for large platforms and frames and I now envisage procedures similar to FORM-SORM for computing attrition in M-FREL.

Discussions at the Universities of Pisa and Waterloo have also made it clear that lengths of specified cracks do not fully specify the degradation of a structure so that a complete description should also include "damage" parameters such as hole elongation, wear and corrosion if any of these interact with more standard parameters in a way that varies with crack history. The present structure of M-FREL does allow this generality but the inclusion of extra cycles from fretting or buckling effects (Section 2.2) is more difficult.

In the Laboratories visited there is little work being devoted to crack/crack interaction except for Rooke's compounding method and more experimental results from Purdue; much of the theoretical and survey work has already been published. At present the compounding method is the favoured theoretical basis in M-FREL. For crack rate prediction the journey yielded fresh information from Ditlevson and from Cox which is still to be studied.

In general fatigue four of the six laboratories are testing Aluminium-Lithium alloys and fatigue simulations have started to allow for mettalurgical structure (ITAM and Rockwell).

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TABLE I IFIP PROGRAMME

WEDNESDAY MORNING, MAY 6

09.00 - 10.30	Registration
10.30 - 10.45	OPENING SESSION
10.45 - 11.00	Coffee
11.00 - 12.30	SESSION A M.J. Baker,
	A1 Degradation of Brittle, Redundant Structural Systems *F. Guers, K. Dolinski & R. Rackwitz*, F. R. Germany
	A2 Failure Mode Enumeration for System Reliability Assessment by Optimization Algorithms *A. M. Nafday & R. B. Corotis*, U.S.A.
	A3 Sensitivity Measures in Systems Reliability *P. Bjerager*, Denmark
12.30 - 14.00	Lunch

WEDNESDAY AFTERNOON, MAY 6

13.15 - 14.00	Meeting for Working Group members
14.00 - 15.30	SESSION B Y.Murotsu
	B1 Optimal Bridge Design by Geometric Programming *N. C. Das Gupta, H. Paul & Y. C. Hui*, Singapore
	B2 An Application of Fuzzy Linear and Nonlinear Programming to Structural Optimization *K. Koyama & Y. Kamiya*, Japan
	B3 Integrated Reliability-Based Optimal Design of Structures *J. D. Sørensen & P. Thoft-Christensen*, Denmark
15.30 - 16.00	Coffee
16.00 - 17.30	SESSION C O.Ditlevsen
	C1 On the Calibration of ARMA Processes for Simulation *S. Krenk*, Denmark
	C2 Reliability Analysis of Discrete Dynamic Systems under Non-Stationary Random Excitations *T. Chmielewski*, Poland
	C3 Reliability Analysis of Hysteretic Multi-Storey Frames under Random Excitation *S. R. K. Nielsen, K. J. Mørk & P. Thoft-Christensen*, Denmark
	C4 The Information Processing in Stochastic Structural Dynamics *K. Sobczyk*, Poland
19.00	Reception at the Old City Hall

THURSDAY MORNING, MAY 7

09.00 - 10.30 SESSION D R.Rackwitz

D1
Reliability Computations for Rigid Plastic Frames with General Yield Conditions
O. Ditlevsen, Denmark

D2
Structural System Reliability Analysis Using Multi-Dimensional Limit State Criteria
M. J. Baker & R. Turner, United Kingdom

D3
Structural Safety Evaluation of Steel-Jacket Platforms
Y. Guenard, France

10.30 - 11.00 Coffee

11.00 - 12.30 SESSION E K.Sobczyk

E1
On the Application of a Nonlinear Finite Element Formulation in Structural Systems Reliability
J. Amdahl, B. Leira & Y.-L. Wu, Norway

E2
Probabilistic Fracture Mechanics Applied to the Reliability Assessment of Pipes in a PWR
T. Schmidt & U. Schomburg, F. R. Germany

E3
Reliability of Fiber Bundles under Random Time-Dependent Loads
M. Grigoriu, USA

12.30 - 13.30 Lunch

THURSDAY AFTERNOON, MAY 7

13.30 - 19.00 North Sea Tour

A North Sea bus tour has been arranged on Thursday, May 7 from 13.30 - 19.00. The programme will to some extent depend on the weather, but a visit to the »Nordsøcenter» in Hirtshals is included in the tour. The bus will depart from the University at 13.30 and pick up accompanying persons from Slotshotellet at 13.45. It will return to Slotshotellet not later than 19.00. The cost is included in the conference fee.

20.00 Conference Dinner

An informal Working Conference dinner will take place in the restaurant »Papegøjehaven» (see the map on the last page of this folder).

The North Sea Tour and the Conference Dinner are free for those who have paid the conference fee. Accompanying persons can participate in the tour and the dinner by paying Dkr. 450. Tickets can be obtained in the secretariat.

FRIDAY MORNING, MAY 8

09.00 - 10.30 SESSION F R. Corotis

F1
Modelling of the Strain Softening in the β-Unzipping Method
W. Paczkowski, Poland

F2
Contribution to the Identification of Dominant Failure Modes in Structural Systems
Y. Murotsu & S. Matsuzaki, Japan

F3
Reliability of Ideal Plastic Systems Based on Lower-Bound Theorem
H. O. Madsen, Norway

F4
Reliability of Partially Damaged Structures
V. Costa, Portugal

10.30 - 11.00 Coffee

11.00 - 12.30 SESSION G Henrik O. Madsen

G1
Parallel Systems of Series Subsystems
T. Egeland, Norway

G2
Application to Marine Structures of Asymptotic Stationary Vector Process Methods
R. Cazzulo, Italy

G3
On some Graph-Theoretic Concepts and Techniques Applicable in the Reliability Analysis of Structural Systems
A. Vulpe & A. Carausu, Romania

12.30 - 14.00 Lunch

FRIDAY AFTE...OON, MAY 8

14.00 - 15.30 SESSION H M. Grigoriu

H1
A Program to Predict Fatigue in Structures with Several Cracks
D. G. Ford, Australia

H2
Reliability Estimates by Quadratic Approximation of the Limit State Surface
A. Naess, Norway

H3
Calibration Basis for Structural Glass Design
N. Lind, Canada

15.30 CLOSING SESSION

TIME TABLE FOR SAS FLIGHTS TO COPENHAGEN FRIDAY EVENING, MAY 8:

Flight No.	SK212	SK214	SK216
Departure Aalborg	17.20	19.45	22.05
Arrival Copenhagen	18.05	20.30	22.50

CONFERENCE SECRETARIAT
Conference director: *P. Thoft-Christensen*. Conference secretary: *Kirsten Aakjær*.
Address: Institute of Building Technology and Structural Engineering, University of Aalborg, Sohngaardsholmsvej 57, DK-9000 Aalborg, Denmark.
Telephone: +45 - 8 - 14 23 33.
Telex: 69790 AUB DK.

TABLE II ATTENDEES AT IFIP CONFERENCE

J. Almlund
Statoil
P. O. Box 300
N - 4001 Stavanger
Norway

J. Amdahl
SINTEF
Avd. for Konstruksjonsteknikk
N - 7034 Trondheim - NTH
Norway

M. J. Baker
Dept. of Civil Engineering
Imperial College
London SW7 2BU
United Kingdom

P. Bjerager
ABK, Building 118
Technical University of Denmark
DK-2800 Lyngby
Denmark

A. Carausu
Str. Dr. V. Babes 8
R - 6600 IASI - 6
Romania

I. Cavanagh
University of Aalborg
Sohngaardsholmsvej 57
DK-9000 Aalborg
Denmark

R. Cazzulo
Registro Italiano Navale
Via Corsica 12
I - 16128 Genova GE
Italy

T. Chmielewski
Technical University of Opole
ul. Zamiejska 19
PL - 45-851 Opole
Poland

R. Corotis
Dept. of Civil Engineering
The Johns Hopkins University
Baltimore, Maryland 21218
USA

T. Dahlberg
Solid Mechanics
Chalmers University of Technology
S - 412 96 Göteborg
Sweden

M. Delmar
University of Aalborg
Sohngaardsholmsvej 57
DK - 9000 Aalborg
Denmark

O. Ditlevsen
ABK, Building 118
Technical University of Denmark
DK - 2800 Lyngby
Denmark

T. Egeland
University of Oslo
Inst. of Mathematics, Dept. C
Box 1053, N - 0316 Oslo
Norway

M. H. Faber
University of Aalborg
Sohngaardsholmsvej 57
DK - 9000 Aalborg
Denmark

D. G. Ford
Aeronautical Research Labs.
GPO Box 4331
Melbourne 3001, Victoria
Australia

M. Grimmelt
MAN Technologie GmbH
Dachauer Strasse 667
D - 8000 Munich 50
Federal Republic of Germany

Y. Guenard
SNEA(P)
CSTS - Chemin Larribau
F - 64000 Pau
France

N. C. Das Gupta
Dept. of Civil Engineering
National University of Singapore
Singapore 0511

Y. Kamiya
Dept. of Civil Engineering
Shinshu University, Wakasato 500
Nagano City, Nagano 380
Japan

I. S. Kountouris
Dept. of Civil Engineering
Imperial College
London SW7 2BU
United Kingdom

K. Koyama
Dept. of Civil Engineering
Shinshu University, Wakasato 500
Nagano City, Nagano 380
Japan

S. Krenk
ABK, Building 118
Technical University of Denmark
DK - 2800 Lyngby
Denmark

I. Langen
Statoil
P. O. Box 300
N - 4001 Stavanger
Norway

N. Lind
Dept. of Civil Engineering, E2,
University of Waterloo
Waterloo, ON
Canada N2L 3G1

R. Løseth
Veritas Research
P. O. Box 300
N - 1322 Høvik
Norway

H. O. Madsen
Veritas Research
P. O. Box 300
N - 1322 Høvik
Norway

M. Michelsen
Rambøll & Hannemann A/S
Kjærulfsgade 2
DK - 9400 Nørresundby
Denmark

Y. Murotsu
University of Osaka Prefecture
Dept. of Aeronautical Engineering
Sakai, Osaka 591
Japan

K. Mørk
University of Aalborg
Sohngaardsholmsvej 57
DK - 9000 Aalborg
Denmark

A. Naess
Dept. of Civil Engineering
Norwegian Inst. of Technology
N - 7034 Trondheim - NTH
Norway

S. R. K. Nielsen
University of Aalborg
Sohngaardsholmsvej 57
DK - 9000 Aalborg
Denmark

H. Nordal
Statoil, P. O. Box 300
N - 4001 Stavanger
Norway

W. Paczkowski
ul. Cedynska 22/7
PL - 71-570 Szczecin
Poland

G. B. Pirzada
Dept. of Civil Engineering
Mehran University
College of Engineering & Technology
Nawabshah, Sind
Pakistan

R. Rackwitz
Technical University of Munich
Arcisstrasse 21
D - 8000 Munich 2
Federal Republic of Germany

T. Schmidt
Technische Mechanik
Universität der Bundeswehr
P. O. Box 700822
D - 2000 Hamburg 70
Federal Republic of Germany

G. Sigurdsson
University of Aalborg
Sohngaardsholmsvej 57
DK - 9000 Aalborg
Denmark

J. D. Sørensen
University of Aalborg
Sohngaardsholmsvej 57
DK - 9000 Aalborg
Denmark

P. Thoft-Christensen
University of Aalborg
Sohngaardsholmsvej 57
DK - 9000 Aalborg
Denmark

R. Turner
Dept. of Civil Engineering
Imperial College
London SW7 2BU
United Kingdom

L. Tvedt
Veritas Research
P. O. Box 300
N - 1322 Høvik
Norway

V. Valgeirsson
University of Aalborg
Sohngaardsholmsvej 57
DK - 9000 Aalborg
Denmark

A. Vulpe
Str. Ralet 7
R - 6600 IASI - 6
Romania

Y. - L. Wu
Inst. for Marine Konstruksjoner
Norges tekniske Høgskole
N - 7000 Trondheim
Norway

LATE REGISTRATION

V. Costa
Rua Joaquim Antonio de Aguiar 27
P - Lisboa 1200
Portugal

M. Grigoriu
367 Hollister Hall
Cornell University
Ithaca, N. Y. 14853
U.S.A.

R. Haak
Messerschmitt-Bölkow-Blohm GmbH
Postfach 950109
D - 2103 Hamburg 95
Federal Republic of Germany

R. Ranganathan
Dept. of Civil Engineering
Imperial College
London SW7 2BU
United Kingdom

K. Sobczyk
Inst. Fund. Techn. Res.
ul. Swietokrzyska 21
PL - 00-049 Warsaw
Poland

ORGANIZING COMMITTEE

M. J. Baker, United Kingdom
H. O. Madsen, Norway
Y. Murotsu, Japan
R. Rackwitz, Federal Republic of Germany
P. Thoft-Christensen, Denmark (conference director)

CONFERENCE SECRETARIAT

Conference director: *P. Thoft-Christensen.* Conference secretary: *Kirsten Aakjær.*

Address: Institute of Building Technology and Structural Engineering, University of Aalborg, DK - 9000 Aalborg, Denmark. Telephone: International + 45 - 8 - 14 23 33. Telex: 69790 AUB DK.

TABLE III ICASP PROGRAMME

INTERNATIONAL SCIENTIFIC COMMITTEE

Niels C. Lind, Waterloo, Ontario (Chairman)
Giuliano Augusti, Roma, Italy
K. Biernatowski, Wroclaw, Poland
Victor F.B. de Mello, Sao Paulo, Brasil
Luis Esteva, Mexico D.F., Mexico
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Owen G. Ingles, Tasmania, Australia
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M. Matsuo, Nagoya, Japan
A. Nowak, Ann Arbor, Michigan
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Richard Campanella, University of British Columbia, Vancouver (Co-Chairman)
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Colin Brown, University of Washington, Seattle

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Civil Engineering Department, University of Waterloo
Institute for Risk Research, University of Waterloo
Natural Sciences and Engineering Research Council
U.S. National Science Foundation

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ADDENDUM TO LIST OF PARTICIPANTS, AS OF MAY 22, 1987

ADDITIONAL PARTICIPANTS

Barry ANDERSON
Transmission Engineer
B.C. HYDRO
1190 Brockton Place
North Vancouver, B.C. CANADA V7G 2E6

Mr. Peter BENNETT
Dysan Perins Lab
South Parks Road
Oxford, ENGLAND OXI 32Y

Mr. Duane CASTANEDA
U. of Washington
Dept. of Civil Engineering
Seattle, Washington USA

Mr. Marcello CIAMBOLI
Dept. of Structural Engineering
University of Rome
ITALY

Dr. A. DAVENPORT
University of Western Ontario
Boundary Layer Wind
Tunnel Lab
London, Ontario CANADA N6A 5B9

Mr. Ian JORDAAN
Memorial Univ. ty of Newfoundland
ST. Johns, Nfld. A1B 3X5 CANADA

Mr. Ashish KARAMCHANDANI
P. O. Box 2024
Stanford University
Stanford, California USA 94305

Anne KIREMIDJIAN
Dept. of Civil Engineering
Stanford University
Stanford California USA 94305

Mr. Ivar LANGEN
Professor
Statoil PO Box 300
N4001, Stavanger NORWAY

Mr. Joseph SWEENEY
Oxford University
Dysan Perins Lab
South Parks Road
Oxford, England OX1 32Y UK

Dr.D.G.FORD Melbourne Australia

Shannon TAO
4343 San Cristo Place
Victoria, B.C. V8N 5G5 CANADA

Mr. Steve WINTERSTEIN
PO Box 2024
Stanford University
Stanford, California USA 94305

CANCELLATIONS

Prof. Marvin E. Criswell
Colorado State University
Fort Collings, Colorado USA

Mr. Achintya HALDAR
Georgia Inst. of Technology
Atlanta, GA USA

Mr. Yoshihisa Kanatani
Chubu Electric Power Co., Inc.
Nagoya, JAPAN

Prof. Kunio Kawamura
Kanazaswa Inst. of Tech.
Ishikawa, JAPAN

Mr. P.H.S.W. KULATILAKE
University of Arizona
Tucson, Arizona USA

Dr. K. RAMACHANDRAN
Imperial College
London, UK

A

Dr. Elfatih M. ALI
UNIVERSITY OF KHARTOUM
Dept. of Civil Engineering
Khartoum
SUDAN

Mr. Joseph ALLWARDEN
Department of Civil Engineering
UNIVERSITY OF MAINE
103 Boardman Hall
Orono, ME USA 04473
(2107) 581-2182

Prof. Eduardo E. ALONSO
TECHN. UNIV. OF CATALUNYA
J. Girona Salgado 31
Barcelona-S.
SPAIN 8034
(93) 204-8252

Prof. S.T. ARIARATNAM
UNIVERSITY OF WATERLOO
Solid Mechanics Div., Faculty of Eng.
Waterloo, ONT
CANADA N2L 3G1
(519)885-1211

Mr. Angel ARTEAGA
CECIME. CSIC
Serrano, 123
Madrid SPAIN 28006

Prof. Akira ASAOKA
NAGOYA UNIVERSITY
Furo-cho, Chikusa-ku
Nagoya, Aichi
JAPAN
(052)781-5111

Prof. Giuliano AUGUSTI
UNIV. DI ROMA LA SAPIENZA
Fac.Ingegneria, Via Eudossiana 18
Rome ITALY184
(39)6-461366

Prof. Bilal AYYUB
UNIVERSITY OF MARYLAND
Dept. of Civil Engineering
College Park, MD. USA 20742
301-454-2211

Mr. Robert AZZOUZ
UNIV. DE CLERMONT II
24, ave. des Landais BP 45
Aubiere FRANCE 63170
73264110 p3762

B

Prof. R. BAKER
TECHNICON, ISRAEL INST OF TEC
Dept.of Geotechnology
Haifa ISRAEL
(03)292323

Prof. Alberto BERNARDINI
UNIV.D. STUDI PADOVA
Ist.Sc.Costr., Via F. Marzolo 9
Padova ITALY 35100

Mr. Glen BESTERFIELD
NORTHWESTERN UNIV.
Dept. of Mech. & Nuclear Eng.
Evanston, IL. USA 60201
(312)491-5642

Prof. Kazimierz BIERNATOWSKI
TECHN. UNIV. of WROCLAW
Polish Committee on Geotechnics
Wroclaw POLAND P-53-651
202964

Dr. Peter BJERAGER
TECHNICAL UNIV. OF DENMARK
Dept. of Structural Engineering
Lyngby DENMARK DK-2800
45-2-883511

Prof. Rafael BLAZQUES
Dept. of Civil Engineering
UNIVERSITY OF CALIFORNIA, BERKELEY
629 Lexington Avenuea, Apt. 3
El Cerrito, CA USA 94530
(415) 642-2469

Dr. F. BLJUGER
ISRAEL INST. OF TECHN.
Building Research Station
Haifa ISRAEL 32000
04-293026

Dr. David I. BLOCKLEY
UNIVERSITY OF BRISTOL
Dept. of Civil Engineering
Bristol U.K. BS8 1TR
0272-303283

Mr. Albert BOLLE
UNIVERISTY OF LIEGE
Quai Banning, 6
Liege, BELGIUM 4000
(41) 52080

Dr. Philippe L. BOURDEAU
SWISS FED. INST. OF TECHN.
Soil Mechnics Lab. ISRF-LMS, EPFL
Lausanne SWITZERLAND CH-1015
(21)472315

Mr. Richard BOURQUARD
GROUND ENG.&TEST. SERV. INC.
4784 First Ave. North
Birmingham, AL. USA 35222
(205)591-4340

Prof. Franco BRAGA
IST.DI SCIENZA CONSTUZIONI
Via N. Sauro 85
Potenza, PZ. ITALY 85100
(06)3285331 home

Mr. David BROOMHEAD
KLOHN LEONOFF
10180 Shellbridge Way
Richmond, B.C. V6X 2W7
(604) 273-0311

Mr. Hubert N. BROSSEAU
CGS
4198 Hingston Ave.
Montreal, P.O.
CANADA H4A 2J7
(514)333-5151

Mr. Bill BULLEIT
MICHIGAN TECHN.UNIV.
Dept. of Civil Engineering
Houghton, MI. USA 49931
906-487-2522

Mr. Steinar BYSVEEN
SAGA PETROLEUM A/S
Mavles vei 20
Hovik NORWAY N-1322
(02)126829

C

Mr. E.O.F.CALLE
DELFT GEOTECHNICS
P.O.BOX 69
Delft NETHERLANDS 2600AB
31-015-569223

Dr. Dick CAMPANELLA
UNIVERSITY OF B.C.
Dept. of Civil Engineering
Vancouver, B.C.
CANADA V6T 1W5
(604)228-4266

Mr. Claudio CARINO
UNIVERSITY OF PAVIA
Via Abbiategrasso 209
27100 Pavia, ITALY

Prof. Fabio CASCIATI
UNIVERSITY OF PAVIA
Via Abbiategrasso 209
Pavia ITALY I-27100
(0382)391458

Mr. Xing CHEN
UNIVERSITY OF FUZHOU
Dept. of Civil Engineering
Fuzhou, Fujian"
P.R.of China

Mr. Claudio CHERUBINI
UNIV. DEGLI STUDI DI BARI
Fac. Ingegneria-Ist.di Geologia
Bari TALY

Prof. Lan-Yu CHOU
SIAN COLLEGE OF HIGHWAYS
Civ.Eng.,Bldg.58,S.C.,No.3 Tsuihua-Ru
Sian, Shaanxi P.R.of CHINA 710031
52927-371

Dr. Karen C. CHOU
SYRACUSE UNIVERSITY
Dept. of Civil Engineering
Syracuse, N.Y.
USA 13244
(315)423-3314

Mr. George CHRISTAKOS
UNIV. of KANSAS, GEOL. SURVEY
1930 Constant Ave., Campus West
Lawrence, Kansas
USA 66046
913-864-4991

Prof. Allin CORNELL
STANFORD UNIVERSITY
110 Conquito Way
Portola Valley, CA.
USA 94025
(415)854-8053

Prof. Ross B. COROTIS
THE JOHNS HOPKINS UNIV.
Dept. of Civil Engineering
Baltimore, Maryland
USA 21218
301-338-7719

Mr. C.B.H. CRAGG
ONTARIO HYDRO RESEARCH DIV.
800 Kipling Avenue
Toronto, ONT.
CANADA M8Z 5S4
(416)231-4111

Mr. R. CUNLIFFE
CARLETON UNIVERSITY
Dept. of Civil Eng.
Ottawa, ONT.
CANADA K1S 5B6
(613)564-7400

D

Prof. H. Joseph DAGHER
UNIV. OF MAINE
Dept.of Civil Eng., 303 Boardman Hall
Orono, Maine
USA 04469
(207)581-2138

Dr. Ari DANAY
ONTARIO HYDRO
700 University Avenue
Toronto, Ontario M5G 1X6
(416) 592-5289

Dr. A. DAVENPORT
UNIVERSITY OF WESTERN ONTARIO
Boundary Layer Wind
Tunnel Lab
London, ONTARIO N6A 5B9
(519) 661-3338

Prof. Armen DER-KIUREGHIAN
UNIVERSITY OF CALIFORNIA
725 Davis Hall
Berkeley, CA. USA 94720
415)642-2469

Mr. Robert DICKINSON
UNIVERSITY OF WATERLOO
Dept. of Systems Design
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UNIVERSITY OF PALERMO
Dip. Ingegneria Strutturale & Geotecnica
Palermo, ITALY 90128
091-427166

Mr. Ove DITLEVSEN
TECHNICAL UNIV.OF DENMARK
Dept.of Structural Eng., Building 118
Lyngby, DENMARK DK-2800
(02)883511/5261

Mr.Mauro DOLCE
IST. DI SCIENZA CONSTRUZIONI
Uiversita dell'Aquila
Monteluco di Roio, AQ.
ITALY 67100
(06)634274 home

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Mr. Bruce ELLINGWOOD
JOHNS HOPKINS UNIV.
Dept. of Civil Engr.
34th.& Charles St.
Baltimore, MD USA 21218-2699
(301)338-8443

Prof. Hans A. ESCHENAUER
UNIVERSITY OF SIEGEN
Inst.of Mechanics & Control Eng.
D 59 Siegen, N.W. W. Germany 5900
(0271)740-4641

F

Prof. Lucia FARAVELLI
UNIVERSITY OF PAVIA
Via Abbiategrasso 209
Pavia ITALY I-27100
(0382)391459

Mr.Jean-Claude FAUGERAS
UNIVERSITE DE CLERMONTII
Rech.Genie Civil,
24 Av.des Landais
Aubiere, FRANCE F-63170
73-264110

Prof. Jean-Louis FAVRE
ECOLE CENTRAL DE PARIS
Lab. de Mecanique des Sols-Structures
Chatenay-Malabry
FRANCE 92295 CEDEX
(1)46613310

Dr. William M. FLEISCHMAN
VILLANOVA UNIVERSITY
Dept. of Mathematical Sciences
Villanova, PA." USA 19085
215-645-4964

Dr. Claudio FLORIS
POLITECNICO DI MILAN
Dp.Strutt.Eng.,Plazza L.da Vinci 32
Milan, ITALY 20133
(02)23994203

Mr. Bryan FOLZ
UNIVERSITY OF B.C.
Depatment of Civil Engineering
VAncouver, B.C. CANADA V6T 1W5

Mr. Ricardo O.FOSCHI
UNIVERSITY OF B.C.
Dept. of Civil Engineering
Vancouver, B.C. CANADA V6T 1W5
(604)228-2560

Mr. Dan M. FRANGOPOL
UNIV.OF COLORADO AT BOULDER
Dept. of Civil Engineering
Boulder, Colorado USA 80309-0428
(303)492-7165

Dr. Yozo FUJINO
UNIVERSITY OF TOKYO
Dept. of Civil Eng., Bunkyo-ku
Tokyo, JAPAN 113
(03)812-2111

MR. M.E.M. FUJITA
Member of JSCE
Schwaneckstr. 8
800 Munchen WEST GERMANY

Dr. Hitoshi FURUTA
KYOTO UNIVERSITY Civ.Eng.
Yoshida-honmachi,Sakyo-ku
Kyoto, Kyoto JAPAN 606
(+81)75-751-2111

G

Mr. Dario A. GASPARINI
CASE WESTERN RESERVE UNIV.
University Circle - Bingham Bldg.
Cleveland, Ohio USA 44106
(216)368-2699

Dr. A. GENS
JORTE GIRONA SALGADO
Civil Engineering School
#31 Barcelona SPAIN 08034

Prof.K.P.GEORGE
THE UNIVERSITY OF MISSISSIPPI
Civil Engr.Dept.
University, MS. USA 38677
(601)232-5365

Prof. Renato GIANNINI
UNIVERSITA DI ROMA
Via Gramsci 53
Roma, ITALY 197
(06)873791

Mr. Rob GILLARD
MANHIRE CUNLIFFE PARTNERSHIP
Carleton Univ., Dept. of Civil Eng.
Ottawa, ONT. CANADA K1S 5B6
(613)564-7400

Mr. Juan Jose GONI
TULANE UNIVERSITY
New Orleans, Louisiana
USA 70118
(504) 865-5776

Mr. Francois GUERS
2 Rue Grennette
Annecy, FRANCE 74 000
(33) 50654141 P. 4700

H

Dr.Fabian HADIPRIONO
OHIO STATE UNIVERSITY
2070 Neil Ave.
Columbus, Ohio USA 43210
614-292-8518

Mr. Tarik HADJ-HAMOU
TULANE UNIVERSITY
Dept. of Civil Engineering
New Orleans, LA. USA 70118
(504)865-5778

Ms. Carol HAMMOND
USDA FOREST SERVICE
Intermountain Res.St.
1221 S.Main St.
Moscow, Idaho USA 83843
(208)882-3557

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UNIVERSITY OF COLORADO
1951 Grandview Apt. D.
Boulder, CO USA 80302
(303) 492-8561

Dr. Paul C.HOFFMAN
VILLANOVA UNIVERSITY
Civil Engineering Departm ϶nt
Villanova, PA. USA 19085
215-645-4964

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TAKENAKA TECHN.RES.LAB.
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Prof. Masaru HOSHIYA
MUSASHI INST. OF TECHNOLOGY
1-23 Tamazutsumi Setagaya-ku
Tokyo, JAPAN
03-703-3111/479

I

Mr. Kewnji IKEJIMA
UNIVERSITY OF COLORADO, BOULDER
Dept. of Civil Engineering
Campus Box 428
Boulder, Colorado USA 80309-0428
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NAGOYA UNIV., Dept.of Architect
Furo-cho, Chikusa-ku
Nagoya, Aichi JAPAN 464
(052)781-5111

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NAGOUA UNIV., Dept.of Architect
Furo-cho, Chikusa-ku
Nagoya, Aichi JAPAN 464
(052)781-5111

Dr. Samy KRISHNASAMY
ONTARIO HYDRO
800 Kipling Ave KB223
Toronto, Ont. CANADA M8Z 5S4
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Tucson, Arizona USA 85721
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1455 De Maisonneuve Blvd.West
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Campbell, A.C.T." AUSTRALIA 2600
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Prof. W.D. LIAM FINN
UNIV. OF BRITISH COLUMBIA
Dept. of Civil Eng., 2324 Main Mall
Vancouver, B.C. CANADA V6T 1W5
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Via Eudossiana 18
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200 Bloomfield Ave.
West Hartford, C.T. USA 6117
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UNIV. OF WATERLOO
Dept. of Civil Engineering
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519-885-1211

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Mr. Borg MADSEN
Civil Engineering
UNIV. OF BRITISH COLUMBIA
2324 Main Mall
VAncouver, B.C. CANADA V6T 1W5
(604 987-3430

Dr. Henrik O. MADSEN
VERITAS RESEARCH
PO Box 300
Hovik, NORWAY 1322
(47) 2477547

Mr. Magdi H. MANSOUR
DALHOUSIE UNIVERSITY
Dept. of Civil Engineering
Halifax, N.S. CANADA B3H 3.5
(902)424-8874

Mr. Shigeyuki MATSUHO
TOTTORI UNIVERSITY
Dept. of Ocean Civil Eng.
Koyama-cho, Minami 4-101
Tottori, JAPAN 680
(0857)28-0321

Prof. Minoru MATSUO
NAGOYA UNIVERSITY
Furo-cho,Chikusa-ku
Nagoya, Aichi JAPAN 464
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Dept. of Civil Eng. & Surveying
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CRACOW TECHN. UNIVERSITY
31-155 Krakow
Krakow, POLAND 31-525
(012)330300/324

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UNIVERSITY OF PALERMO
Dip. Ingegneria Strutturale & Geotecnica
Palermo, ITALY 90128
091-427121

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UNIVERSITY OF IDAHO
Dept. of Civil Engineering
Moscow, Idaho USA 83843
(208)885-6961

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WORCESTER POLYTECHNIC INST.
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Worcester, MA. USA
(617)793-5534

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UNIVERSITY OF MICHIGAN
Dept. of Civil Eng.
2340 G.G. Brown
Ann Arbor, MI. USA 48109
(313)764-9299

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UNIVERSITY OF ROME
Via A. Gramsci 53
Rome, ITALY 00197
(06) 87 3791

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Mr. Keith ORTIZ
UNIVERSITY OF ARIZONA
Aerospace/Mechanical Engr.Dept.
Tucson, AZ USA 85721
(602)621-6093

Mr. Jacques OUELLET
ECOLE POLYTECHNIQUE
Dep.Genie Mineral, C.P.6079
Succ-"A" Montreal, P.Q.
CANADA H3C 3A7
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Queen's Bldg., University Walk
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(0272)303030

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IST.UNIV.DI ARCHITETT.VENEZIA
Corso Duca degli Abruzzi 24
Torino, TALY 10129
(011)556-7833

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UNIVERSITY OF ROME
Via A. Gramsci, 53
Rome, ITALY 197
(0039)6-873791

Dr. Chandra PUTCHA
TRW One Space Park
Redondo Beach, CA. SA 90278
(213)217-3132

R

Dr. R. RACKWITZ
TECHN. UNIV. MUNCHEN
Lab.f.Konstrukt.Ingenieurbau
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Lexington, KY. USA 40506
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UNIVERSITY OF B.C.
Civil Engineering Dept.
Vancouver, B.C. CANADA V6T 1W5
(604)228-3998

S

Prof. Jun SAKAMOTO
NAGOYA UNIV.
Dept.of Architect
Furo-cho, Chikusa-ku
Nagoya, Aichi JAPAN 464
(052)781-5111

Mr. J.S. SALINAS
CARLETON UNIVERSITY
Dept. of Civil Eng.
Ottawa, ONT. CANADA K1S 5B6
(613)564-7400

Mr. Erwin SCHWING
Dipl. Ing.
UNIVERSITAT KARLSRUHE
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COLUMBIA UNIVERSITY
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New York, New York 10027 USA
(212) 280-3892

Dr. Wataru SHIRAKI
TOTTORI UNIVERSITY Civ.
Engr.,Koyama-cho,Minami 4-101
Tottori, JAPAN 680
(0857)28-0321

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INST. TEKNOLOGI BANDUNG
Jl. Ganesha 10 (Jurusan Sipil)
Bandung, Jabar INDONESIA

Mr. Nicholas SITAR
UNIVERSITY OF CALIFORNIA, BERKELEY
Dept. of Civil Engineering
440 Davis Hall
Berkeley, CA USA 94720
(415) 643-8623

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Geotechnical Consultant
20 Riccarton Cresc.
Currie,MID., Scotland U.K. EH145PA
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Centro Investigacion Natematica Y
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Prof. Michel SOULIE
UNIVERSITY DE MONTREAL
Ecole Polytechnique
Civil Engineering Department
Montreal, Quebec CANADA M3C 3A7
(514) 340-4791

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RICE UNIVERSITY
Dept. of Civil Eng.
P.O.Box 1892
Houston, TX. USA 77251
(713)527-4909

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VERITEC
PO Box 300
Hoevik, NORWAY N-1322

Mr. David STONE
KLOHN LEONOFF
10180 Shellbridge Way
Richmond, B.C. V6X 2W7
(604) 273-0311

Mr. Toshiyuki SUGIYAMA
YAMANASHI UNIVERSITY
Takeda 4-3-11
Kofu, Yamanashi JAPAN 400
(0552)52-111

Mr.Masatoshi SUZUKI
NIKKEN SEKKEI LTD. JSSMFE
5-15-18 Kugayama-ku
Tokyo, JAPAN 168
(03)813-3361

T

Prof. Paul N. TAKAOKA
TOTTORI UNIV.
DEPT.CIVIL ENG
680 Tottori shi, Koyama ...
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(0857)28-0321

Prof. Andrew G. TALLIN
POLYTECHNIC UNIVERSITY
Dept. of Civil Entineering
333 Jay Street
Brooklyn, N.Y. USA 11201
(718) 643-2223

Prof. Robert Y. TAN
NAT. TAIWAN UNIV.
Dept. of Civil Engineering
Taipei TAIWAN, ROC 107

Mr. Gaetano TANCREDI
UNIVERSITA DI ROMA
Fac. Ingegneria
Via Eudossiana, 18
Rome, ITALY 00184
(06) 4740266

Dr. Wilson H. TANG
UNIV. OF ILLINOIS AT URBANA
208 N. Romine
Urbana, IL USA 61801
(217)333-6954

Mr. Yasunaga TATSUMI
STANFORD UNIVERSITY
J.A.Blume Earthquake Engineering Ctre.
Stanford, CA. USA 94305-4020
(415)723-1009

Prof. P. THOFT-CHRISTENSEN
UNIVERSITY OF AALBORG
Sohngaardsholmsvej 57
Aalborg, DENMARK DK-9000
(08)14233

Prof. George TSIATAS
WASHINGTON STATE UNIV.
Dept.of Civil & Environmental Eng.
Pullman, WA. USA 99164-2914
509-335-5438

Mr. Hideo TSUBOI
FUDO CONSTRUCTION CO.
5-30,Hirano-cho,Higashi-ku"
Osaka, JAPAN 541
(06)201-1121

Mr. Carl TURKSTRA
POLYTECHNIC UNIVERSITY
Dept. of Civil Eng.
333 Jay Str."
Brooklyn, N.Y. USA 11201
718-643-8958

V

Mr. J. van HETEREN
ROAD & HYDRAULIC ENG.DIV.
P.O.Box 5044
Delft, GA. NETHERLANDS 2600GA
(070)264101

Dr. Erol VAROGLU
FORINTEK CANADA CORP.
6620 N.W. Marine Drive
Vancouver, B.C." CANADA V6T 1X2
604-224-3221

Dr. Charles VITA
GOLDER ASSOCIATES, INC.
4101-148th Ave., N.E.
Redmond, WA. USA 98052
(206)883-0777

W

Prof. Y.K. WEN
UNIV. OF ILLINOIS, URBANA
3118 NCEL N. Romine
Urbana, Illinois USA 61801
(217)333-1328

Mr. Thomas E. WOLFF
MICHIGAN STATE UNIV.
Dept. of Civil Engineering
East Lansing, MI. USA 48824
(517)355-8422

Prof. Shue Tuck WONG
SIMON FRASER UNIVERSITY
Dept. of Geography
Burnaby, B.C. CANADA V5A 1S6
(604)291-3712

Mr. Tien H. WU
OHIO STATE UNIVERSITY
2070 Neil Ave.
Columbus, Ohio USA 43210
(614)292-1071

Y

Dr. Masaaki YAMAMOTO
KAJIMA CORP
Shinjuku Mitsui Bldg. 1-1 2-Chome
Nishi-Shinjuku, Tokyo JAPAN 163
3-344-2111

Mr. Z.C. YAO
UNIVERSITY OF B.C.
Dept. of Civil Engineering
Vancouver, B.C. CANADA V6T 1W5

Z

Dr. Masoud M. ZADEH
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16. ABSTRACT

During May 1987 the author presented a paper, "Range-Pair Exceedances in Stationary Gaussian Processes" to the First IFIP Conference, "Reliability and Optimisation of Structural Systems" at Aalborg, Denmark.

This memo describes this Conference, the better known ICASP5 and discussions at six establishments visited during the same trip.

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